

# Dissipation effects on the superconductor-insulator transition in 2-D superconductors

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Results on the superconductor to insulator transition in two-dimensional films are analyzed in terms of coupling of the system to a dissipative bath. Upon lowering the temperature the parameter that controls this coupling becomes relevant and a wide range of metallic phase is recovered.

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Quantum phase transitions (QPT) continue to attract intense theoretical and experimental interest. These transitions – where changing an external parameter in the Hamiltonian of the system induces a transition from one quantum ground state to another, fundamentally different one – have been invoked to explain data from various experiments, including quantum-Hall liquid to insulator, metal to insulator and superconductor to insulator experiments. In this paper we use experiments done on thin superconducting films which undergo a so-called Superconductor-Insulator (SI) transition to propose a new phase diagram for a QPT that includes a dissipation axis. The implications of our analysis go much beyond this problem and in fact bear on all QPT in two dimensions.

The most common treatment of the SI transition is to map it onto the so-called “dirty-bosons” model. In this model Cooper pairs are the Bose particles with well formed (non-fluctuating) pair amplitudes. At zero temperature an SI transition is expected as a function of disorder, with vortex-antivortex pairs activated by both quantum fluctuations and disorder. Vortices of one vorticity are also induced by a magnetic field; with no disorder an Abrikosov lattice of these vortices realizes the superconducting phase. However, an arbitrary amount of disorder disrupts the lattice and a true superconducting phase is assumed to be recovered only at  $T=0$ . In the superconducting phase vortices are localized into a so-called vortex-glass phase [3] and the Cooper pairs are delocalized. Upon increasing the magnetic field above some critical field  $H_c$ , vortices will delocalize with Cooper pairs localizing into a Bose-Glass phase. Further increase of the magnetic field dissociates the Cooper pairs, and fermion degrees of freedom then determine the properties of the system. At the SI transition, both vortices and Cooper pairs are delocalized in a “Bose-Metal” phase; thus, a finite conductivity is expected at the transition. The above scenario was the basis for a scaling theory proposed by Fisher [3] in which a field-tuned transition was considered as a continuous transition with an associated diverging length  $\xi \sim (H_c - H)^{-\nu}$ , as well as a finite, universal conductivity at the transition [4].

The above “dirty-bosons” model was used to describe numerous experimental data in both disorder and field tuned transitions [1,5,6]. However, a difficulty in applying this model arose when the vortex glass phase displayed a temperature independent resistance that could

be interpreted as quantum tunneling of vortices [2,7,8]. In particular, in previous experiments on amorphous MoGe [1] we showed scaling for a range of disorder; yet the superconducting phase at lower fields showed finite resistance indicative of quantum tunneling of vortices [2]. Assuming continuity as a function of increasing magnetic field, we concluded that there was no true superconducting phase all the way to the critical field. A closer inspection of the data presented in [1] and [2] suggests that while the quantum critical point is apparent at low temperatures with excellent agreement with scaling, lowering the temperature further results in a rapid disruption of scaling. We interpret these results as evidence of a coupling of our system to a dissipative environment, presumably a background of delocalized fermions as was first conjectured by Yazdani and Kapitulnik [1].

Such coupling to dissipation could lead to a new phase diagram for the system, shown pictorially in figure 1. To the standard H-T-disorder phase diagram [3], we add a new axis,  $\alpha$ , representing the strength of the coupling to a dissipative bath (so the figure is a slice at fixed disorder). Upon cooling the system the coupling to the bath becomes more relevant and the system flows away from the unstable critical point (the pure dirty bosons point) into a wide range of “metallic” behavior. In fact, depending on the system, the opening of the metallic region could leave a diminishingly small region where true superconductivity can be found. In the case of MoGe with  $R_{\square}$  of order 1.5 k $\Omega$  we showed [2] that already at 20% of  $H_c$ , superconductivity is lost.

Continuing to use amorphous-MoGe films as our model system, we have conducted further measurements to better examine the low temperature “metallic” behavior and dissipative coupling. These experiments were performed on thin films grown by multitarget magnetron sputtering on a SiN substrate with a Ge buffer layer. The films were grown in the same sputtering runs as those used in [2] and [1]; details of growth and characterization are described elsewhere [9]. Most of the data reported in this paper was taken on films with  $x=0.43$ , thickness of 30 Å and  $T_c \sim 0.5$  K. Previous studies have determined the films to be highly amorphous and homogeneous over all relevant length scales. The films were patterned into 4-probe structures, and measured in a dilution refrigerator using standard low-frequency lock-in techniques. Care was taken to eliminate spurious noise and heating effects. A typical set of resistance vs. temperature for

increasing magnetic field data is given in figure 2. Similar results were obtained for all films including those reported in [1,2]. A main feature of these result is that upon lowering the temperature the activated behavior of the resistance changes to a temperature independent resistance as the temperature approaches zero, as can be seen in the  $\log R_{\square}$  vs.  $1/T$  inset of figure 2. In [2] the low temperature saturation value of the resistance obeys the empirical form

$$R(H) = R_0 e^{c(\hbar/e^2 R_{\square})H/H_c^2}, \quad (1)$$

with  $R_{\square}$  being the resistance per square of the sample and  $c \simeq 2$  is a constant. This unusual behavior was explained by Shimshoni *et al.* [10] using dissipative quantum tunneling of vortices from one “insulating” puddle to its neighbor. The source of dissipation was assumed to be the electrons in the core of the vortex, suggesting the use of Bardeen-Stephen [11] expression for the viscosity in the Euclidian action governing the tunneling. If the vortex tunneling is mediated by coupling to a dissipative bath, then finite diffusion appears which explains the flattening of the resistance as  $T$  approaches zero. This model produces excellent fit to the experimental data (e.g., the theoretical model, using Bardeen-Stephen dissipation gives  $c \simeq 1.6$  for the prefactor). Since the superconducting phase is obtained in this model by percolation of couplings of superconducting puddles, this model also explains the exponent  $\nu \simeq 1.35$  found in all field-tuned transitions by many groups since the correlation-length exponent in 2-D classical percolation is  $4/3$ .

To check the scaling and flattening of the resistance in the MoGe films, we extended the temperature range by measuring down to 20 mK from low field through the presumed SI transition. A blow-up of the transition region is shown in figure 3. Here we observe that as we go to low temperatures, all curves, whether initially decreasing or increasing, flatten. This affects scaling in a dramatic way. Following [3] we fit isotherms for  $T \geq 100$  mK to:  $R = R_c \mathcal{F}[(H - H_c)/T^{1/z\nu}]$ . The scaling function  $\mathcal{F}(x)$  displays two branches, for positive (“insulating”) and negative (“superconducting”) arguments. A best fit to the scaling function for high temperature isotherms gives  $z\nu = 1.33 \pm 0.05$ , as shown in the upper part of figure 4. The dotted line in the figure shows the deviation of the 50mK line from the other scaled curves. This deviation, which evinces the breakdown of scaling with respect to the critical point, is amplified in the lower part of figure 4. We believe that this low temperature deviation from scaling and flattening of the resistance are a manifestation that the isolated metallic point at  $H_c$  “opens-up” to a region of metallic behavior as a function of some parameter that becomes relevant at low temperatures. Adding the hypothesis of vortex tunneling in a dissipative medium we conclude that the natural parameter that “pulls” the system away from the SI transition critical point is the strength of the coupling to the dissipative bath. Starting with a system with fixed disorder

we naturally arrive at the phase diagram presented in figure 1. Note that the phase diagram allows for a finite range of  $\alpha$  in which the SI transition is preserved, a feature that we discuss next.

Dissipation in connection with the S-I transition was first studied by Chakravarty *et al.* [12,13] with a quantum statistical mechanics model of an array of resistively shunted Josephson junctions. This model predicted a superconducting to normal-state transition as a function of dissipation. More recently Wagenblast *et al.* [14] attempted to explain non-universal results observed in experiments on homogeneous [1] and inhomogeneous thin films [5] by introducing a model with local dissipation in which the dissipative term couples only to the phase of a single island. Their model led to a new universality class at the superconductor-insulator transition. In particular, they found that the conductivity at criticality is non-universal and is characterized by a damping-dependent dynamical critical exponent. Both models [13,14] preserve the SI transition but do not allow for a range of a metallic phase. Along with the fact that neither model includes disorder (in [12] randomness was discussed and argued not to change the nature of the phase diagram), we believe that the absence of dual excitations (i.e. vortices) in the treatment of the transition excludes a finite range of metallic phase. In the absence of vortices, a metallic phase is excluded automatically, according to our proposed scenario as outlined below [15]. However, in the absence of dissipation and for strong enough disorder a pure SI transition is expected according to [3] and thus we allow for a range,  $\alpha < \alpha_c$ , for which a metallic phase exists only at the transition point itself. For weak disorder this range may be very small, as is presumably the case for the MoGe films discussed here.

Levelling of the resistance – and therefore a probable coupling to dissipation – in field tuned transitions has been observed in other experiments on thin superconducting films [7] and in Josephson Junctions arrays [8]. Even more intriguing is the fact that the analogous problem of the quantum Hall effect to insulator transition (QHIT) exhibits similar effects. In this problem a sharp change in the behavior of the resistivity at low temperature as a function of the magnetic field has been interpreted as a quantum phase transition between localized bosons and localized vortices [16]. While scaling has been observed with high accuracy for this problem [17], recent experiments reveal that occasionally samples fail to exhibit scaling, and the resistance on the quantum Hall liquid side levels to a constant, suggesting quantum tunneling [19].

Quantum tunneling of vortices in the SI transition problem, or of edge states in the QHIT problem, are a natural consequence of the Shimshoni *et al.* model [10]. This model predicts continuous transitions for the SI transition or QHIT cases which are percolation-like. Its importance is that it allows for a destruction of the superfluid phase due to incoherent tunneling of vortices (in the SI transition) or of edge states (in the QHIT).

The missing ingredient of the model is the existence of a dissipative bath to which the system may couple with some strength  $\alpha$ . This deficiency, which is corrected in the present paper, leads to the generalized phase diagram presented in figure 1. Combining the percolation model of [10], the argument of [12] that in the random array model the transition is governed by the properties of the typical junction, and the argument of Schmid [18] that depending on the parameters of the junction its behavior will change from coherent to diffusive, it seems that a metallic phase must exist in the SI problem. A similar argument should hold for the QHIT problem. However, for samples in which the dissipation is weak the QHIT may still be preserved, as has been observed by many authors [22]. In these cases it is no surprise that the resistance at the critical field is the quantum resistance,  $h/e^2$ , and that the exponent is  $\nu \sim 7/3$ , a value consistent with quantum percolation. The failure to observe scaling in samples that show flattening of the resistance [19] is interpreted as an indication that a stronger  $\alpha$  exist in these samples. We therefore suggest that for these samples scaling should be attempted with the high temperatures data only. This should lead to a result similar to the one presented here for the SI transition with  $\nu \sim 4/3$ . In fact, following our prediction we examined figure 3(a) of [19], which presented the asymptotical behavior of the activation energy in the QH state. This activation energy is proportional to  $T^{1/z\nu}$  and gives  $1/z\nu \simeq 3/4$ , very different from other QHIT results of  $3/7$  or  $3/14$ . While scaling is observed in this high temperature limit, the critical resistance is different from the universal resistance, similar, again, to the SI results. Dephasing in the QHIT problem on the insulating side was discussed by Pryadko and Auerbach [23] resulting in a finite Hall resistivity at  $T=0$ . However, the source of dissipation is still unknown in this problem.

Finally we comment that our discussion above is very general and should apply to any two-dimensional quantum critical point where dissipation can be relevant. A possible candidate is the newly discovered metal-insulator transition in Si MOSFETs. Here the insulator is believed to be a Wigner crystal. In the presence of disorder this problem resembles that of a vortex glass in the SI transition problem.

In conclusion, in this paper we presented a new phase diagram for the superconductor-insulator transition problem in the presence of coupling to a dissipative bath. We argued that as the critical point is approached by e.g. lowering the temperature, this coupling may become a relevant variable in the problem and thus pull the system to a new phase which is metallic in nature. We further proposed that this scenario is very general and may explain the recent results on flattening of the resistance observed in quantum Hall to insulator transitions.

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- [1] A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. 74, 3037 (1995).
  - [2] D. Ephron, A. Yazdani, A. Kapitulnik, and M.R. Beasley, Phys. Rev. Lett. 76, 1529 (1996)
  - [3] M.P.A. Fisher, Phys. Rev. Lett. 65, 923 (1990).
  - [4] M.P.A. Fisher, G. Grinstein, and S.M. Girvin, Phys. Rev. Lett. 64, 587 (1990); K. Kim and P.B. Weichman, Phys. rev. B 43, 13583 (1991).
  - [5] D.B. Haviland *et al.* Phys. Rev. Lett. 62, 2180 (1989); J.M. Valles, R.C. Dynes, and J.P. Garno, Phys. Rev. Lett. 69, 3567 (1992).
  - [6] A.F. Hebard and M.A. Paalanen, Phys. Rev. Lett. 65, 927 (1990).
  - [7] Y. Liu, D.B. Haviland, L.I. Glazman, and A.M. Goldman, Phys. Rev. Lett. 68, 2224 (1992).
  - [8] H.S.J. van der Zant, W.J. Elion, L.J. Geerligs, and J.E. Mooij, Phys. Rev. B 54, 10081 (1996); C.D. Chen, P. Delsing, D.B. Haviland, Y. Harada, and T. Claeson, Phys. rev. B 51, 16645 (1992).
  - [9] S. Yoshizumi, W. L. Carter, and T. H. Geballe, J. Non-Cryst. Solids 61/62, 589 (1984).
  - [10] E. Shimshoni, A. Auerbach and A. Kapitulnik, Phys. Rev. Lett. 80, 3352 (1998).
  - [11] J. Bardeen and M.J. Stephen, Phys. Rev. 140, A1197 (1965).
  - [12] S. Chakravarty, G-L. Ingold, S. Kivelson, and A. Luther, Phys. Rev. Lett. 56, 2303 (1986).
  - [13] S. Chakravarty, G-L. Ingold, S. Kivelson, and G. Zimanyi, Phys. Rev. B 37, 3283 (1988).
  - [14] K-H. Wagenblast, A. van Otterlo, G. Schoen and G. Zimanyi, Phys. Rev. Lett. 78, 1779 (1997).
  - [15] We thank Debopriya Das for discussions of this point.
  - [16] M.P.A. Fisher and D.H. Lee, Phys. rev. B 39, 2756 (1989); D.H. Lee and M.P.A. Fisher, Int. J. of Mod. Phys. B 5, 2675 (1991); S. Kivelson, D.H. Lee, and S.-C. Zhang, Phys. Rev. B 46, 2223 (1992).
  - [17] For a review see S.L. Sondhi, S.M. girvin, J.P. Carini, and D. Shahar, rev. Mod. Phys. 69, 315 (1997).
  - [18] A. Schmid, Phys. Rev. Lett. 51, 1506 (1983).
  - [19] D. Shahar, M. Hilke, C.C. Li, D.C. Tsui, S.L. Sondhi, J.E. Cunningham, and M. Razeghi, Sol. St. Comm. 107, 19 (1998).
  - [20] Y. Imry and S.-K. Ma, Phys. Rev. Lett. 35, 1399 (1975).
  - [21] D.B. Chklovskii, B.I. Shklovskii, and L.I. Glazman, Phys. Rev. B 46, 4026 (1992); D.B. Chklovskii and P.A. Lee, Phys. Rev. B 48, 18060 (1993).
  - [22] For an extensive list of experiments showing scaling in the QHE problem see e.g. Sondhi *et al.* [17].
  - [23] L.Pryadko and A.Auerbach, preprint cond-mat/9808062.

FIG. 1. Phase diagram for the field-tuned SI transition: H-T-Dissipation strength diagram at finite disorder.  $\alpha_c$  marks the point at which a finite range of metallic phase opens up.

FIG. 2. Set of resistance vs. temperature curves for  $B=2,1.3,1.23,1.18,1.1,1.0,.75,.70,0$  Tesla Inset:  $\log R_{\square}$  vs  $1/T$  for  $0,.6,.7,.75,1,1.18,1.21$  Tesla

FIG. 3. Set of resistance vs. temperature curves for  $B=1.3,1.26,1.23,1.21,1.2,1.18$  Tesla. Flattening of the resistance at low temperatures coincides with breakdown of scaling.

FIG. 4. Upper: Scaling for  $T \geq 100$  mK yielding:  $z\nu=1.33\pm0.05$ . 50mK curve (dotted line) strongly deviates from others. Lower: Deviation of scaled curves from “standard” (100mk) curve. Note that only the low temperature curves show significant deviation.







